CDF Wjj anomaly as a non-perturbative effect of the electro-weak interaction

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(Dated: October 17, 2011)

The recently reported CDF excess at $120 - 160\, GeV$ in invariant mass distribution of jet pairs accompanying W-boson [1] is tentatively interpreted as a bound state of two W decaying to quark-anti-quark pair. Non-perturbative effects of EW interaction obtained by application of Bogoliubov compensation approach lead to such bound state due to existence of anomalous three-boson gauge-invariant effective interaction. The application of this scheme gives satisfactory agreement with existing data without any adjusting parameter but the bound state mass $145\, GeV$.

PACS numbers: 12.15.-y; 12.15.Ji; 14.70.Fm; 14.80.Ec

In works [2–8], N.N. Bogoliubov compensation principle [9, 10] was applied to studies of a spontaneous generation of effective non-local interactions in renormalizable gauge theories.

In particular, papers [7, 8] deal with an application of the approach to the electro-weak interaction and a possibility of spontaneous generation of effective anomalous three-boson interaction of the form

$$-\frac{G}{3!}\cdot \epsilon_{abc}\, W^a_{\mu\nu}\, W^b_{\nu\rho}\, W^c_{\rho\mu}\,; \qquad (1)$$
$$W^3_{\mu\nu}\,=\,\cos\theta_W\, Z_{\mu\nu}\,+\,\sin\theta_W\, A_{\mu\nu}\,;$$

with uniquely defined form-factor $F(p_i)$. It was done of course in the framework of an approximate scheme, which accuracy was estimated to be $\simeq (10-15)\%$ [2]. Effective interaction (1) is usually called anomalous three-boson interaction and it is considered for long time on phenomenological grounds [11, 12]. Note, that the first attempt to obtain the anomalous three-boson interaction in the framework of Bogoliubov approach was done in work [13]. Our interaction constant G is connected with conventional definitions in the following way

$$G\,=\,-\,\frac{g\,\lambda}{M_W^2}\,; \qquad (2)$$

where $g \simeq 0.65$ is the electro-weak coupling. The current limitations for parameter λ read [14]

$$\lambda\,=\,-\,0.016^{+0.021}_{-0.023}\,;$$
$$-\,0.059 < \lambda < 0.026\,(95\%\, C.L.)\,. \qquad (3)$$

Interaction (1) increases with increasing momenta p and corresponds to effective dimensionless coupling being of the following order of magnitude

$$g_{eff}\,=\,\frac{g\,\lambda\,p^2}{M_W^2}\,. \qquad (4)$$

Thus for sufficiently large momentum interaction (1) becomes strong and may lead to physical consequences analogous to that of the usual strong interaction (QCD). In particular bound states and resonances constituting of W-s (W-hadrons) may appear. Let us estimate the typical scale for the effect. We know that in QCD upper bound of a region of really strong interaction (non-perturbative region) is around $600\, MeV$ where $\alpha_s \simeq 0.5$ that is coupling $g_s = \sqrt{4\pi\alpha_s} = 2.5$. So we have to equate g_{eff} (4) to this value and define the typical value p_{typ} that gives

$$p_{typ}\,=\,M_W\sqrt{\frac{g_{eff}}{g\,\lambda}}\,\simeq 650\, GeV\,; \qquad (5)$$

where we have taken for modulus of λ its maximal value from limitation (3). Now we have the lightest hadron – the pion with mass $\simeq 140\, MeV$ for typical scale $600\, MeV$ in QCD and for estimated p_{typ} (5) we have possible mass of the lightest W-hadron

$$M_{min}\,=\,\frac{p_{typ}\, M_\pi}{600\, MeV}\,\simeq 150\, GeV\,; \qquad (6)$$

The excess detected in work [1] is situated just in this region. So one might try to consider interpretation of effect [1] as a manifestation of a W-hadron.

In the present work we apply these considerations along with some results of work [8] to data indicating on an excess in jet pair production accompanied by W at TEVATRON [1] in region of jj invariant mass $120 - 160\, GeV$. Some indications for state with the same mass at LHC are discussed in work [15].

Let us assume that this excess is due to existence of bound state X of two W. This state X is assumed to have spin 1 and weak isotopic spin also 1. Then vertex of XWW interaction has the following form

$$\frac{G_X}{2}\,\epsilon_{abc}\, W^a_{\mu\nu}\, W^b_{\nu\rho}\, X^c_{\rho\mu}\,\Psi\,; \qquad (7)$$

where Ψ is a Bethe-Salpeter wave function of the bound state. The main interactions forming the bound state are just non-perturbative interactions (1, 7). This means that we take into account exchange of vector boson W as

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well as of vector bound state X itself. In diagram form the corresponding Bethe-Salpeter equation is presented in Fig. 1. For small mass M_X of state X we expand the kernel of the equation in powers of M_W^2 and M_X^2 and obtain the following equation

$$\Psi(x) = \frac{G^2+G_X^2}{32\pi^2}\int_0^{Y_0}\Psi(y)y dy - \frac{G^2+G_X^2}{32\pi^2}\biggl(\frac{1}{12x^2}\int_0^x\Psi(y)y^3dy - \frac{1}{6x}\int_0^x\Psi(y)y^2dy - \frac{x}{6}\int_x^{Y_0}\Psi(y)dy + \frac{x^2}{12}\int_x^{Y_0}\frac{\Psi(y)}{y}dy\biggr) + \frac{g\,G}{4\,\pi^2}\biggl(\int_0^{Y_0}\Psi(y)dy - \frac{3}{8x^3}\int_0^x\Psi(y)y^3dy + \frac{7}{8x^2}\int_0^x\Psi(y)y^2dy - \frac{1}{2x}\int_0^x\Psi(y)ydy + \frac{x}{8}\int_x^{Y_0}\frac{\Psi(y)}{y}dy - \frac{x^2}{8}\int_x^{Y_0}\frac{\Psi(y)}{y^2}dy)\biggr) - \frac{\mu\,\bar G\sqrt{2}}{\pi}\biggl(\int_0^{Y_0}\Psi(y)dy - \frac{1}{12x^2}\int_0^x\Psi(y)y^2dy + \frac{1}{6x}\int_0^x\Psi(y)ydy + \frac{x}{6}\int_x^{Y_0}\frac{\Psi(y)}{y}dy - \frac{x^2}{12}\int_x^{Y_0}\frac{\Psi(y)}{y^2}dy\biggr) - \frac{\chi\,\bar G\sqrt{2}}{\pi}\biggl(\frac{1}{24}\int_0^{Y_0}\Psi(y)dy - \frac{1}{192x^3}\int_0^x\Psi(y)y^3dy + \frac{1}{64x}\int_0^x\Psi(y)ydy + \frac{x}{64}\int_x^{Y_0}\frac{\Psi(y)}{y} - \frac{x^3}{192}\int_x^{Y_0}\frac{\Psi(y)}{y^3}dy\biggr). \quad \mu = \frac{\bar G\,M_W^2}{16\pi\,\sqrt{2}}\,;\ \chi = \frac{\bar G\,M_X^2}{16\pi\,\sqrt{2}}\,;\ \bar G = \sqrt{G^2+G_X^2}\,. \tag{8}$$

Here $x = p^2$ is the external momentum squared and y is the integration momentum squared. Gauge electro-weak coupling g enters due to diagrams of the second line of Fig. 1. Upper limit Y_0 is introduced for the sake of generality due the experience of works [2–8], according to which Y_0 may be either ∞ or some finite quantity. That is Y_0 is defined in a process of solving an equation. From the physical point of view an effective cut-off Y_0 bounds a "low-momentum" region where our non-perturbative effects act and we consider the equation at interval $[0,\, Y_0]$ under condition

$$\Psi(Y)\,=\,0\,. \tag{9}$$

For interaction (1) Y_0 is defined in work [8].

We shall solve equation (8) by iterations. Let us perform the following substitution

$$z\;=\;\frac{(G^2+G_X^2)x^2}{512\pi^2}\,,\quad t\;=\;\frac{(G^2+G_X^2)y^2}{512\pi^2}\,; \tag{10}$$

then equation (8) takes the following form

$$\Psi(x)\equiv\Psi_0(z) = 8\int_0^{z_0'}\Psi_0(t)dt - \frac{2}{3z}\int_0^z\Psi_0(t)tdt + \frac{4}{3\sqrt{z}}\int_0^z\Psi_0(t)\sqrt{t}\,dt + \frac{4\sqrt{z}}{3}\int_z^{z_0'}\frac{\Psi_0(t)}{\sqrt{t}}dt - \frac{2z}{3}\int_z^{z_0'}\frac{\Psi_0(y)}{y}dy + \frac{g'\sqrt{2}}{4\,\pi}\biggl(8\int_0^{z_0'}\frac{\Psi_0(t)}{\sqrt{t}}\,dt - \frac{3}{z\sqrt{z}}\int_0^z\Psi_0(t)tdt + \frac{7}{z}\int_0^z\Psi_0(t)\sqrt{t}dt - \frac{4}{\sqrt{z}}\int_0^z\Psi_0(t)dt + \sqrt{z}\int_z^{z_0'}\frac{\Psi_0(t)}{t}dt - z\int_z^{z_0'}\frac{\Psi_0(t)}{t\sqrt{t}}dt\biggr) - \mu\biggl(16\int_0^{z_0'}\frac{\Psi_0(t)}{\sqrt{t}}\,dt - \frac{4}{3z}\int_0^z\Psi_0(t)\sqrt{t}\,dt + \frac{8}{3\sqrt{z}}\int_0^z\Psi_0(t)dt + \frac{8\sqrt{z}}{3}\int_z^{z_0'}\frac{\Psi_0(t)}{t}dt - \frac{4z}{3}\int_z^{z_0'}\frac{\Psi_0(t)}{t\sqrt{t}}dt\biggr) - \chi\biggl(\frac{2}{3}\int_0^{z_0'}\frac{\Psi_0(t)}{\sqrt{t}}\,dt - \frac{1}{12z\sqrt{z}}\int_0^z\Psi_0(t)tdt + \frac{1}{4\sqrt{z}}\int_0^z\Psi_0(t)dt + \frac{\sqrt{z}}{4}\int_z^{z_0'}\Psi_0(t)dt - \frac{z\sqrt{z}}{12}\int_z^{z_0'}\frac{\Psi_0(t)}{t^2}dt\biggr);\quad \Psi_0(0)\,=\,1\,; \tag{11}$$

$$R\,=\,\frac{G_X^2}{G^2}\,;\quad z_0' = \frac{(G^2+G_X^2)Y_0^2}{512\pi^2}\,=\,(1+R)\,z_0\,;\quad g' = \frac{g}{\sqrt{1+R}}\,. \tag{12}$$

Here we shall use results of work [8] according to which consideration of the compensation equation for effective

interaction (1) we obtain definite value for $z_0 = 9.6175$ and value for $g(M_W)$ being consistent with experimental value $g(M_W) = 0.65$. Thus, we use these values in the forthcoming calculations.

$$z_0 \,=\, 9.6175\,; \quad g = g(M_W) = 0.65\,. \tag{13}$$

Let us formulate the first approximation to equation (11). The first five terms of rhs of (11) will present the simplest zero approximation. Then we substitute into terms being proportional to g', μ', χ' a solution of the zero approximation and take into account constant terms and terms being proportional to $\sqrt{z}$, $\sqrt{z}\,ln\,z$. Terms being $O(z\,lnz)$ and smaller (for small z) are neglected. Just this approximation was used in works [7, 8].

The zero approximation evidently reads

$$\Psi_{00}(z) = \frac{\pi}{2}\,G_{15}^{21}\big(z|^{0}_{1,0,1/2,-1/2,-1}\big)\,. \tag{14}$$

Here the solution is expressed in terms of a Meijer function [16]. Then set of equations (11) takes the form

$$\begin{aligned}
&\Psi_0(z) = INH - \frac{2}{3z}\int_0^z \Psi_0(t)tdt + \frac{4}{3\sqrt{z}}\int_0^z \Psi_0(t)\sqrt{t}\,dt + \frac{4\sqrt{z}}{3}\int_z^{z_0'} \frac{\Psi_0(t)}{\sqrt{t}}dt - \frac{2z}{3}\int_z^{z_0'}\frac{\Psi_0(y)}{y}dy\,;\\
&INH \,=\, 1 - \sqrt{z}\left(\frac{g'\sqrt{2}}{8\,\pi} + \frac{8\,\mu}{3} - \frac{\chi}{4}\right)\left(ln\,z + 4\,\gamma + 4\,ln\,2 + \frac{\pi}{2}\,G_{15}^{21}\big(z_0'|^{0}_{0,0,1/2,-1/2,-1}\big)\right) + \\
&\sqrt{z}\left(\frac{g'\sqrt{2}}{48\,\pi} + \frac{68\,\mu}{9} - \frac{25\,\chi}{32}\right);\\
&1 \,=\, 8\int_0^{z_0'}\Psi_0(t)dt \,-\, \left(\frac{g'\,2\,\sqrt{2}}{\pi} - 16\,\mu + \frac{2\,\chi}{3}\right)\int_0^{z_0'}\frac{\Psi_{00}(t)}{\sqrt{t}}\,dt
\end{aligned} \tag{15}$$

where γ is the Euler constant. Now we look for solutions of set (15) bearing in mind conditions (12) and values (13). We have relation

$$M_X \,=\, M_W\,\sqrt{\frac{\chi}{\mu}}\,; \quad M_W \,=\, 80.4\,GeV\,. \tag{16}$$

We look for the exact solution of set of equations (15) in the following form

$$\begin{aligned}
&\Psi_0(z) = \frac{\pi}{2}\,G_{15}^{21}\big(z|^{0}_{1,0,1/2,-1/2,-1}\big) \,+\\
&C_1\,G_{15}^{21}\big(z|^{1/2}_{1/2,1/2,1,-1/2,-1}\big) \,+\\
&C_2\,G_{04}^{20}\big(z|_{1,1/2,-1/2,-1}\big) \,+\\
&C_3\,G_{04}^{10}\big(-z|_{1,1/2,-1/2,-1}\big)\,.
\end{aligned} \tag{17}$$

Let us choose a solution with "experimental" $M_X = 145\,GeV$ [1], then we have solution with the following parameters

$$\begin{aligned}
&C_1 = -\,0.015282\,; \quad C_2 = -3.26512\,;\\
&C_3 = 1.27962\,10^{-11}\,; \quad g' = 0.03932\,;\\
&\chi = 0.0074995\,; \quad z_0' = 2627.975\,;\\
&\mu \,=\, 0.002305\,.
\end{aligned} \tag{18}$$

Parameters (18) defines the following physical parameters

$$\begin{aligned}
&G \,=\, \frac{0.0099}{M_W^2}\,; \quad \lambda \,=\, -\,\frac{G\,M_W^2}{g} \,=\, -\,0.0152\,;\\
&M_X \,=\, 145\,GeV\,; \quad |G_X| \,=\, \frac{0.1639}{M_W^2}.
\end{aligned} \tag{19}$$

Value λ (19) agrees with restrictions (3). With value of G from (19) we have additional solutions for "radial excitations" X_i with the following masses and coupling constants

$$\begin{aligned}
&M_{X_1} \,=\, 180.7\,GeV\,; \quad |G_{X_1}| \,=\, \frac{0.0628}{M_W^2}\,;\\
&M_{X_2} \,=\, 205.1\,GeV\,; \quad |G_{X_2}| \,=\, \frac{0.1155}{M_W^2}\,.\\
&M_{X_3} \,=\, 244.2\,GeV\,; \quad |G_{X_3}| \,=\, \frac{0.1837}{M_W^2}\,.
\end{aligned} \tag{20}$$

With these masses $X_{1,2,3}$ decay into pair of W-s, i.e.

$$\begin{aligned}
&X^{\pm}_{1,2,3} \,\to\, W^{\pm} \,+ (Z,\gamma)\,; \quad X^{0}_{1,2,3} \,\to\, W^{+} \,+ W^{-}\,;\\
&\Gamma(X_1^0) \,=\, 0.0086\,GeV\,; \quad \Gamma(X_1^{\pm}) \,=\, 0.0051\,GeV\,;\\
&\Gamma(X_2^0) \,=\, 0.126\,GeV\,; \quad \Gamma(X_2^{\pm}) \,=\, 0.083\,GeV\,;\\
&\Gamma(X_3^0) \,=\, 1.26\,GeV\,; \quad \Gamma(X_2^{\pm}) \,=\, 0.89\,GeV\,;\\
&BR(X_1^+ \to W^+Z) = 0.44;\; BR(X_1^+ \to W\gamma) = 0.56.\\
&BR(X_2^+ \to W^+Z) = 0.80;\; BR(X_2^+ \to W\gamma) = 0.20.\\
&BR(X_3^+ \to W^+Z) = 0.91;\; BR(X_3^+ \to W\gamma) = 0.09.
\end{aligned} \tag{21}$$

Now interaction (7) with parameters (19) defines reactions of $X^{\pm}$, X^0 production at TEVATRON and their decays. Bound states X interact with fermion doublets ψ_L due to diagram presented at Fig. 2. The effective interaction is described by the following expression

$$\begin{aligned}
&L_{X\psi} \,=\, g_X\,X^a_\nu\,\bar\psi_L\,\tau^a\,\gamma^\nu\psi_L;\\
&g_X = \frac{g^2\,G_X\,M_X^2}{64\,\pi^2}\int_{\mu^2}^{z_0'}\frac{\Psi_0(t)}{t}\,dt = 0.000879\,.
\end{aligned} \tag{22}$$

Due to interactions (7, 22) there are the following decays of bound states X (in calculations of decay parameters and cross-sections we use CompHEP package [17])

$$X^\pm \to W^\pm + \gamma\,(85.9\%); \quad X^\pm \to j\,j\;(9.5\%); \\ X^0 \to j\,j\;(71.4\%)\,; \qquad (23)$$

where we associate a jet with each quark. The states are narrow, but small total widths do not contradict to data [1] because the observed width of the enhancement corresponds to experimental resolution. One has also to bear in mind that real masses of neutral and charged X may differ by few GeV.

For estimation of X production cross-sections we have to take into account that according to EW gauge invariance isotopic triplet X^a necessarily interacts with gauge field W^a and the interaction vertex is just the gauge one with the same coupling g

$$\Gamma^{abc}_{\mu\nu\rho}(p,q,k) = g\,\epsilon^{abc}\Big(\Phi_\kappa(p,q,k)\,\kappa(g_{\nu\rho}k_\mu - g_{\rho\mu}k_\nu) + \\ \Phi_g(p,q,k)\left(g_{\mu\nu}(q_\rho - p_\rho) - g_{\nu\rho}q_\mu + g_{\rho\mu}p_\nu\right)\Big); \qquad (24)$$

where $\Phi_{\kappa,g}(p_i)$ are form-factors, which are equal to unity for W momentum $k = 0$ and other two momenta p, q on the mass shell, κ is the well-known parameter describing quadrupole interaction of a vector particle. In the present approximation $\kappa = 0$. Effective total energy for partons collisions at TEVATRON is around $300\,GeV$ which is essentially smaller than typical value (5). Thus, for estimates of cross-sections at TEVATRON we take $\Phi_g = 1$ and $\Psi \simeq \Psi(0) = 1$.

So taking into account all relevant interactions (7,22,24) we obtain the following estimates for cross-sections for energy $\sqrt{s} = 1960\,GeV$

$$\sigma(p\bar p \to W^\pm X^0 + ...) = 1.86\,pb\,; \\ \sigma(p\bar p \to W^\mp X^\pm + ...) = 1.71\,pb\,; \\ \sigma(p\bar p \to Z\,X^\pm + ...) = 1.37\,pb\,; \qquad (25) \\ \sigma(p\bar p \to X^0\,X^\pm + ...) = 0.35\,pb\,; \\ \sigma(p\bar p \to X^\mp\,X^\pm + ...) = 0.26\,pb\,.$$

Taking into account branching ratios (23) we obtain for additional Wjj and Zjj production in the region of enhancement the following estimate. We also divide cross-section for $jet - jet$ production into two parts: with accompanying γ and without γ

$$\sigma(p\bar p \to W^\pm + \gamma + 2\,j + ...) = 0.26\,pb\,; \\ \sigma(p\bar p \to W^\pm + 2\,j + ...) = 1.49\,pb\,; \qquad (26) \\ \sigma(p\bar p \to Z + 2\,j + ...) = 0.13\,pb\,.$$

Total cross-section for $Wjj + Wjj\gamma$: $\sigma(Wjj) = 1.75\,pb$ occurs to be rather smaller than result [1] $\sigma(Wjj) = 4.0 \pm 1.2\,pb$, whereas small value for Zjj production quite agrees with [1] data. However recent results of $D0$ [18] do not support large value for $\sigma(Wjj)$ and give upper limit for cross-section under study $\sigma(Wjj) < 1.9\,pb$ (95% C.L.). As a matter of fact our result (26) evidently does not contradict both results, because it differs from CDF number [1] by less than two s.d..

Processes (25) contribute also to observable reactions of pair weak boson production. From (23, 25) we have additional contribution

$$\Delta\big(\sigma(p\bar p \to W^+W^-) + \sigma(p\bar p \to ZW^\pm)\big) = 2.8\,pb\,; \quad (27)$$

that gives no contradiction to data [19] at TEVATRON

$$\sigma(W^+\,W^-) + \sigma(Z\,W^\pm) = 17.4 \pm 3.3\,pb\,; \qquad (28) \\ (\sigma(W^+\,W^-) + \sigma(Z\,W^\pm))_{SM} = 15.1 \pm 0.9\,pb\,;$$

where the lower line corresponds to SM NLO calculations [20]. We see that possible contribution (27) comfortably fits into error bars of difference between experimental and theoretical (SM) numbers (28).

The production of radial excitations X_i may be compared with data on search of resonant WW and WZ production [21]. The results following from values of parameters (20, 21) are the following ($B_i = BR(X_i \to W\,Z)$)

$$X_1 : \sigma B_1 = 0.15\,pb\,;\; X_2 : \sigma B_2 = 0.76\,pb\,; \\ X_3 : \sigma B_3 = 1.64\,pb\,. \qquad (29)$$

These results by no means contradict upper limits of work [21]. Note that X_i production is accompanied by additional boson either W or Z. Thus we predict effects in triple weak boson production: $W^\pm\,W^+\,W^-$, $W^+\,W^-\,Z$, $W^\pm\,Z\,Z$, which are connected with X_i production.

Process $p + p \to W^\pm + \gamma + ...$ was studied at LHC for energy $\sqrt{s} = 7\,TeV$ [22]. The results in comparison to SM calculations are the following

$$\sigma(W^\pm\gamma) = 56.3 \pm 5.0(st) \pm 5.0(sy) \pm 2.3(lu)\,pb\,; \\ \sigma(W^\pm\gamma)_{SM} = 49.4 \pm 3.8\,pb\,. \qquad (30)$$

The cross-sections for production of $X^\pm$ and X^0 at LHC are estimated to be

$$\sigma(p\,p \to W^\pm X^0 + ...) \simeq 7.9\,pb\,; \\ \sigma(p\,p \to W^\pm X^\mp + ...) \simeq 4.7\,pb\,; \\ \sigma(p\,p \to ZX^\pm + ...) \simeq 5.7\,pb\,; \qquad (31) \\ \sigma(p\,p \to X^\mp + ...) \simeq 0.8\,pb\,; \\ \sigma(p\,p \to X^0 ...) \simeq 0.6\,pb\,.$$

These results are just estimation by an order of magnitude due to significant influence of form-factors in interactions (7, 24) at energy of LHC. In calculations we have used average values of form-factors in the region corresponding to the most probable s_{eff} of partons: $\sqrt{s_{eff}} \simeq 700\,GeV$ [23]. Additional contribution from processes (31) to $W^\pm\,\gamma$ production reads

$$\Delta\sigma(W^\pm\gamma) \simeq 9.7\,pb\,. \qquad (32)$$

We see that here we also have no contradiction with data (30). Let us emphasize that this process is quite promising for checking of our scheme, because we not only predict additional contribution (32) but we insist that this additional contribution means production of narrow resonance $X^{\pm}$ with mass around $145\,GeV$ which decays mostly to $W^{\pm}+\gamma$.

Let us present also estimate for production of the $145\,GeV$ excess at LHC for $\sqrt{s}\,=\,7\,TeV$, which follows from processes (31)

$$\sigma(p\,p\,\to\,j\,j\,+...)\simeq 0.5\,pb\,; \qquad (33)$$
$$\sigma(p\,p\,\to\,j\,j\,+\,W^{\pm}\,+...)\simeq 6.1\,pb\,.$$

To conclude we once more would emphasize that the would-be resonances being considered here might serve as an evidence for existence of the new family of particles with mass scale of hundreds GeV – W-hadrons.

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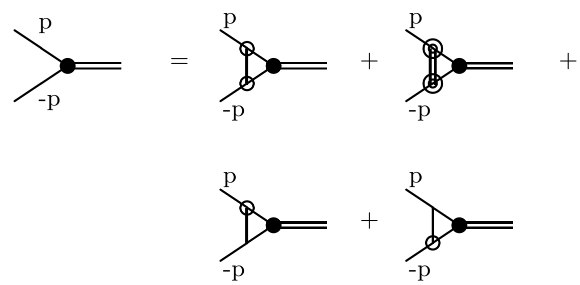

FIG. 1: Diagram representation of Bethe-Salpeter equation for W-W bound state. Black spot corresponds to BS wave function. Empty circles correspond to point-like anomalous three-gluon vertex (1), double circle – XWW vertex (7). Simple point – usual gauge triple W interaction. Double line – the bound state X, simple line – W. Incoming momenta are denoted by the corresponding external lines.

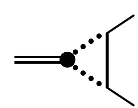

FIG. 2: Diagram for vertex $X\,\bar{q}\,q$. Dotted line – W, double line – bound state X, simple line – a quark. Black spot – the XWW BS wave function.